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Outliers to the peak energy–isotropic energy relation in gamma-ray bursts

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ABSTRACT

The peak energy–isotropic energy (EpEi) relation is among the most intriguing recent discoveries concerning gamma-ray bursts (GRBs). It can have numerous implications for our understanding of the emission mechanism of the bursts and for the application of GRBs to cosmological studies. However, this relation has been verified only for a small sample of bursts with measured redshifts. We propose here a test of whether a burst with an unknown redshift can potentially satisfy the EpEi relation. Applying this test to a large sample of BATSE bursts, we find that a significant fraction of those bursts cannot satisfy this relation. Our test is sensitive only to dim and hard bursts, and therefore this relation might still hold as an inequality (i.e. there are no intrinsically bright and soft bursts). We conclude that the observed relation seen in the sample of bursts with known redshift might be influenced by observational biases and the inability to locate and to localize well hard and weak bursts that have only a small number of photons. In particular, we point out that the threshold for detection, localization and redshift measurement is essentially higher than the threshold for detection alone. We predict that *Swift* will detect some hard and weak bursts that would be outliers to the EpEi relation. However, we cannot quantify this prediction. We stress the importance of understanding the detection–localization–redshift threshold for the coming *Swift* detections.

Key words: gamma-rays: bursts.

1 INTRODUCTION

The detection of gamma-ray burst (GRB) afterglows has enabled the determination of the redshift for a few dozen bursts (out of several thousand observed so far). This has yielded a small sample of bursts for which the *observed* properties can be translated into *intrinsic* ones. This, in turn, has initiated the search for relations between various intrinsic properties. Such relations can have far-reaching implications both for the theoretical understanding of GRBs and for the application of GRBs as a tool.

Even before a large sample of bursts with redshifts was available, it was suggested that the intrinsic peak energy E_{p} and isotropic energy E_{iso} are correlated (Lloyd, Petrosian & Mallozzi 2000; Lloyd-Ronning & Ramirez-Ruiz 2002). Once more than a dozen redshifts had been measured, Amati et al. (2002) reported a tight relation between the isotropic equivalent bolometric energy output in gamma-rays, E_{iso}, and the *intrinsic* peak energy of the νf_ν spectrum, E_{p} (hereafter we denote the E_{p}–E_{iso} relation as EpEi):

$$E_{\mathrm{iso}} = A_k E_{\mathrm{p}}^k , \tag{1}$$

where $k \sim 2$ and A_k is a constant. This result was based on a sample of 12 *BeppoSAX* bursts with known redshifts. 10 additional bursts detected by *HETE II* (Lamb, Donaghy & Graziani 2004; Atteia et al. 2004) supported this result and extended it down to $E_{\mathrm{iso}} \sim 10^{49}$ erg (see also Ghirlanda, Ghisellini & Lazzati 2004a).

Two bursts within the current sample of bursts with a known redshift, GRB 980425 and 031203, are clear outliers to the EpEi relation. Both are dim (low E_{iso}) and hard (high E_{p}). These two bursts are usually ignored as peculiar outliers to a confirmed relation. Even though the EpEi relation is based on a small and unique sample (bursts with a confirmed redshift and a well-observed spectrum), and even though there are two clear outliers, this relation initiated numerous attempts to explain it theoretically and to use it for various applications. Therefore testing the validity of the EpEi relation with the largest available sample (of several thousand BATSE bursts) is extremely important. This is the goal of this Letter.

We present here (equation 5) a simple test of whether a burst can potentially satisfy the EpEi relation. This test can be carried out for bursts with unknown redshift as long as we have a lower limit on the observed peak energy, $E_{\mathrm{p,obs}}$, and an upper limit on the observed bolometric fluence, F. A burst that fails this test must be an outlier satisfying $E_{\mathrm{iso}} < A_k E^k{}_{\mathrm{p}}$. On the other hand, a burst that passes this test does not necessarily satisfy the EpEi relation. One of the known outliers, GRB 980425, fails the test only marginally. However, its low measured redshift puts it as a clear outlier.

First, we apply the test to a larger, but as yet limited, sample of 63 BATSE bursts with unknown redshifts and good spectral data [taken from Band et al. (1993) and Jimenez, Band & Piran (2001)]. We find that at least ∼25 per cent of these bursts

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significantly fail the test and therefore are essentially outliers to the EpEi relation. Next, we consider the full current BATSE catalogue (http://www.batse.msfc.nasa.gov/batse/grb/catalog/current/), for which we test all the long bursts ($T_{90} > 2$ s, where T_{90} is the time over which a burst emits from 5 per cent of its total measured counts to 95 per cent) with complete fluence data in all four energy channels. The exact spectrum for these bursts is unknown, but we can still use the BATSE four-channel data to obtain a lower limit on $E_{\rm p,obs}$ for about half of the bursts. We find that ∼25 per cent of the bursts in the BATSE sample fail the test, and must be outliers to the EpEi relation. The large numbers of outliers that we find in the different samples of BATSE bursts suggest that the EpEi relation is not a generic property of GRBs. Our results do not, however, rule out a possible correlation between $E_{\rm p}$ and $E_{\rm iso}$. We also do not test here the recently suggested relation between $E_{\rm p}$ and the beaming-corrected energy (Ghirlanda et al. 2004a; see, however, Band & Preece 2005).

In Section 2 we present the basic ideas of our analysis. We apply the test to the sample of BATSE bursts with a known peak energy in Section 3 and to the whole BATSE catalogue in Section 4. We discuss the implications of this result, as well as possible reasons why so few outliers were found in the samples of bursts with known redshifts, in Section 5.

2 TRAJECTORIES ON THE ($E_{\rm iso}$, $E_{\rm p}$) PLANE

Consider a burst with known bolometric fluence, F, and observed peak energy, $E_{\rm p,obs}$, but an unknown redshift, z. Assuming a z value, we can evaluate the intrinsic $E_{\rm iso}$ and $E_{\rm p}$. The trajectory of the burst on the ($E_{\rm iso}$, $E_{\rm p}$) plane as we vary z is given by

$$E_{\rm iso} = 4\pi D^2 \tilde{r}_{\rm c}^2(z)(1+z)F, \tag{2}$$

$$E_{\rm p} = (1+z)E_{\rm p,obs}, \tag{3}$$

where $D \equiv c/H_0$ and $\tilde{r}_{\rm c}(z)$ is the dimensionless comoving distance to redshift z. This trajectory represent all the possible values of the intrinsic $E_{\rm p}$ and $E_{\rm iso}$ for given $E_{\rm p,obs}$ and F. On these trajectories, $E_{\rm p} \propto E_{\rm iso}^0$ for small $E_{\rm iso}$ values, while $E_{\rm p} \propto E_{\rm iso}$ for asymptotically large values of $E_{\rm iso}$. Several such trajectories are plotted in Fig. 1.

The EpEi relation (equation 1) is represented by a curve on the ($E_{\rm iso}$, $E_{\rm p}$) plane. For $k \geqslant 1$ (which is satisfied by any reasonable fit to the observed data) there are values of (F, $E_{\rm p,obs}$) for which the trajectories [on the ($E_{\rm iso}$, $E_{\rm p}$) plane] do not intersect the EpEi curve for any value of z. These trajectories correspond to outliers to the EpEi relation (which is not satisfied for any value of z). Put differently, one can imagine using the EpEi relation to determine the redshift of observed bursts. For the bursts that the trajectories do not intersect there will be no value of z for which the EpEi relation is satisfied (Ghirlanda, Ghisellini & Celotti 2004b). A second group of F, $E_{\rm p,obs}$ values are these for which the trajectories intersect the EpEi line. These bursts can potentially satisfy the EpEi relation as there is a possible z value for which this relation can be satisfied. Fig. 1 illustrates the two types of trajectories.

Substituting equations (2) and (3) in equation (1), we obtain a general condition for an intersection between the trajectory of an observed burst and the EpEi line:

$$\frac{A_k}{4\pi D^2}\frac{E_{\rm p,obs}^k}{F} = \frac{r_{\rm c}^2(z)}{(1+z)^{k-1}}. \tag{4}$$

The dimensionless function on the right-hand side depends only on z. It vanishes as z vanishes and at large values of z (for $k > 1$) and hence it has some maximal value denoted C_k. All the bursts for which the observables on the left-hand side are larger than this maximal value are outliers to the EpEi relation. We define a ratio

$$d_k \equiv \frac{A_k}{4\pi D^2 C_k}\frac{E_{\rm p,obs}^k}{F}. \tag{5}$$

(i) Bursts with $d_k < 1$ can potentially satisfy the EpEi relation.

(ii) Bursts with $d_k > 1$ cannot satisfy the EpEi relation. For these bursts, d_k is a measure of the minimal 'distance' of the burst from the EpEi relation. Namely, the observed combination $E_{\rm p}^k/F$ should decrease by this factor in order that the EpEi relation is potentially satisfied.

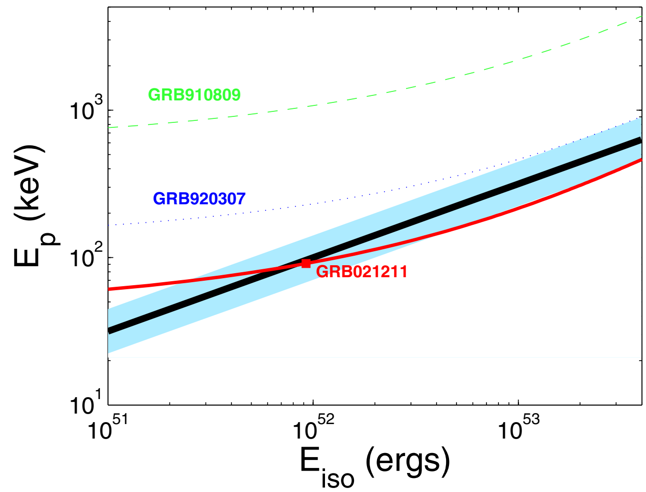

Figure 1. Trajectories of three bursts from Band et al. (1993) and Sakamoto et al. (2004) on the ($E_{\rm iso}$, $E_{\rm p}$) plane. For low redshift values the trajectory is on the left-hand side of the figure as $E_{\rm p} \to E_{\rm p,obs}$ while $E_{\rm iso} \to 0$. As z increases both $E_{\rm p}$ and $E_{\rm iso}$ increase (asymptotically both increase linearly with z) and the trajectory moves to the upper right. The trajectory of GRB 021211 (solid curve) represent a trajectory of a burst consistent with the EpEi relation (for $k = 2$, with $A_2 = 1^{+1}_{-0.5} \times 10^{48}$ erg keV^{-2}) as it intersects the EpEi curve (shaded region). The exact position of GRB 021211 (for which the redshift is known, $z = 1$) on this trajectory is marked with a solid square. The trajectory of GRB 910809 (dashed curve) represent a trajectory of a burst inconsistent with the EpEi relation. It does not intersect the EpEi curve for any value of z. The trajectory of GRB 920307 (dotted curve) is marginally consistent with the EpEi relation.

3 BURSTS WITH A KNOWN OBSERVED PEAK ENERGY

Following the observations (Amati et al. 2002; Lamb et al. 2004; Atteia et al. 2004), we present here (and in Section 4) the results for $k = 2$ with $A_2 = 1^{+1}_{-0.5} \times 10^{48}$ erg keV^2. The error introduced here is our estimate of the spread in the data. All the bursts in the sample of Atteia et al. (2004) are consistent within 1σ with these values. Our results do not change qualitatively for other values of k and A_k that yield a reasonable fit to the data. The cosmological parameters that we consider are $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$, for which $C_2 = 0.56$. For these values we obtain

$$d_2 = 8 \times 10^{-10}\frac{(E_{\rm p,obs}/1\ {\rm keV})^2}{F/(1\ {\rm erg\ cm^{-2}})}. \tag{6}$$

We consider a sample of BATSE bursts [from Band et al. (1993) and Jimenez et al. (2001)] with unknown redshifts for which the observed peak energy has been determined. We consider only bursts with a high spectral index smaller than −2 in order to ensure that the

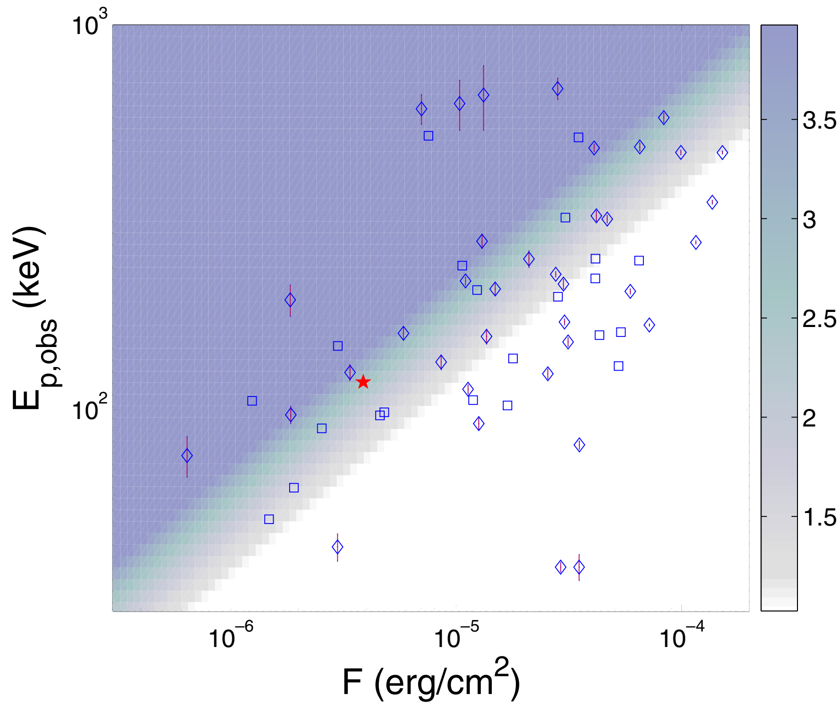

Figure 2. A colour map of d_2. The region marked in white, where $d_2 < 1$, corresponds to allowed solutions of the EpEi relation. Larger values are marked with darker colours and they correspond to the minimal ratio between $E_{\rm iso}$ given by the EpEi relation and $E_{\rm iso}$ given by the ($E_{\rm iso}$, $E_{\rm p}$) trajectory, for the same value of $E_{\rm p}$. Also marked in this figure are values of F and $E_{\rm p,obs}$ for 39 BATSE bursts from Band et al. (1993) (diamonds), and 22 BATSE bursts from Jimenez et al. (2001) (squares). For 29 (15) out of these 61 bursts, $d_2 > 2$ (4). GRB 980425 (solid star symbol) has a marginal $d_2 \approx 3$.

break energy in the observed spectrum is indeed the peak of νF_ν. Our sample includes 63 bursts [40 from Band et al. (1993) and 23 from Jimenez et al. (2001)]. Using the spectral fits for these bursts we derive their bolometric fluence (0.1–10 000 keV).

Fig. 2 depicts a colour map of d_2 for each burst on the (F, $E_{\rm p,obs}$) plane. The observed values of our sample (including error bars where available) are marked on this map. From Fig. 2 it is evident that a significant fraction of the bursts cannot satisfy the EpEi relation. Fig. 3 depicts a histogram of the fraction of bursts with d_2 larger than a given value. We account for uncertainties in the measurement of $E_{\rm p,obs}$, when possible, by using an $E_{\rm p,obs}$ value that is smaller by 1σ than the measured value [unfortunately we can do it only for the Band et al. (1993) sample, since the uncertainties in the measurement of $E_{\rm p,obs}$ are not reported by Jimenez et al. (2001)]. Fig. 3 shows that ≈40 per cent of the bursts have $d_2 > 2$ while 25 per cent of the bursts have $d_2 > 4$ [9/40 from Band et al. (1993) and 6/23 from Jimenez et al. (2001)]. Since the scatter in the EpEi relation is a factor of 2 we consider, conservatively, a burst with $d_2 > 4$ as an outlier. Finally, 13 per cent of the bursts are very far from the relation, having $d_2 > 10$. We stress that these are only lower limits. While bursts for which $d_2 < 1$ can satisfy the EpEi relation, they do not necessarily do so.

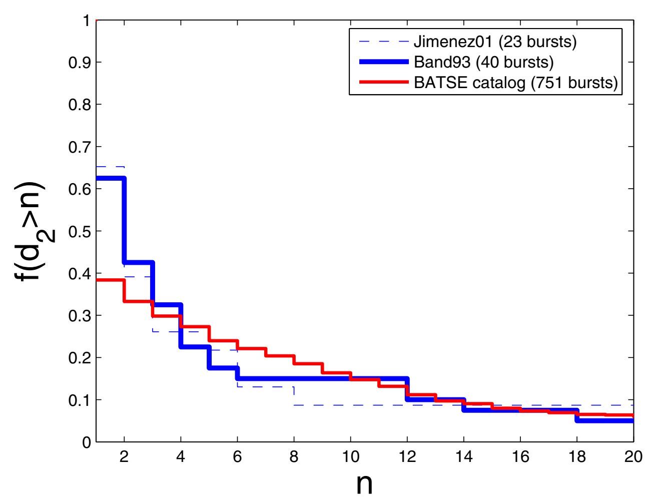

Figure 3. The cumulative fraction of BATSE bursts with $d_2 > n$ as a function of n from the samples of Band et al. (1993) (thick blue line), Jimenez et al. (2001) (dashed line) and the current BATSE catalogue (thin red line). In the last sample (BATSE catalogue) $E_{\rm p,obs}$ was taken as larger than 250 keV for any burst that satisfies equation (7).

4 BATSE BURSTS

Only a small fraction of BATSE bursts have published $E_{\rm p,obs}$ values. Still, we can obtain a lower limit of $E_{\rm p,obs} > 250$ keV for all BATSE bursts for which

$$\frac{F_{300,2000}}{F_{20,50} + F_{50,100} + F_{100,300}} > 1.25, \tag{7}$$

where F_{E_1,E_2} is the fluence between E_1 and E_2 reported in the four BATSE windows. This lower limit holds for the Band et al. (1993) spectra over a wide range of low and high spectral indices (α and β respectively). As a test of the validity and robustness of this criterion, we apply it to the BATSE bursts with known $E_{\rm p}$ (Band et al. 1993; Jimenez et al. 2001, including those with $\beta > -2$ and those with known redshift). We find that indeed all the bursts in the sample, apart from one, that satisfy equation (7) have $E_{\rm p,obs} > 250$ keV (23 bursts in total). Using this lower limit on $E_{\rm p,obs}$ we can obtain a lower limit on d_2 for a large sample of BATSE bursts, where we take

F in the 20–2000 keV energy range (the sum of all four channels) as the bolometric fluence.

We consider a sample of 751 long ($T_{90} > 2$ s) bursts from the current BATSE catalogue (http://www.batse.msfc.nasa.gov/batse/grb/catalog/current/). Our selection criteria were having fluence in all four BATSE bands, having errors that are smaller than half of the measured values in all four bands, and having a measured T_{90}. 361 of these bursts satisfy equation (7), yielding a lower limit on their $E_{\rm p}$. Fig. 3 also depicts the fraction of long bursts out of the sample of 751 bursts that satisfy equation (7) and have $d_2 > n$. We find that approximately 35 per cent of these bursts have $d_2 > 2$, about 30 per cent have $d_2 > 4$ and for 10 per cent this ratio is larger than 15! While this estimate is less robust than the previous ones (i.e. we cannot quantify the error in the lower limit that we obtain for $E_{\rm p,obs}$), it is clear that a significant fraction of long BATSE bursts cannot satisfy the EpEi relation. This result has been confirmed by Band & Preece (2005) who use a sample of 760 BATSE bursts where $E_{\rm p,obs}$ is known.

Finally, we have also performed the same test for the 187 short ($T_{90} < 2$ s) BATSE bursts satisfying the same criteria. These bursts are typically harder than long ones. As they are shorter they also have a lower overall fluence. One could expect that they will not satisfy the EpEi inequality. We find that more than 75 per cent of BATSE short bursts have $d_2 > 10$. Short bursts cannot satisfy the EpEi relation! This result is similar to that obtained by Ghirlanda et al. (2004b).

5 DISCUSSION

We have presented a simple method for testing whether a burst can *potentially* satisfy the $E_{\rm p}$–$E_{\rm iso}$ (EpEi) relation. This method requires only two observables, the bolometric gamma-ray flux and the peak energy. Both can be determined for every observed burst regardless of its localization and redshift determination. We have carried out this test for several samples of BATSE bursts. We find that ≈25 per cent of the BATSE bursts in these samples fail the test and hence they are outliers to the EpEi relation. We stress that this fraction is only a lower limit, as bursts that pass the test may still not satisfy the EpEi relation, once their redshift is known. These results imply that the EpEi relation, in its current form, may not a generic property of GRBs. It is present only in the small sample of bursts with confirmed redshifts and not in the whole sample of observed bursts.

None of the outliers that we find has an isotropic energy larger than the one predicted by the EpEi relation. Truly, our test could not find such bursts. However, the two known outliers have lower isotropic energy than that predicted by the EpEi relation. Moreover, the BATSE data have already demonstrated the absence of soft and bright bursts. The absence of such bursts is confirmed by *BeppoSAX* and *HETE II* which would have easily detected and localized them. Thus we suggest that the common EpEi relation should be replaced by an EpEi inequality:

$$E_{\rm iso} \lesssim A_k E_{\rm p}^k. \tag{8}$$

The natural question that arises is why are there so many outliers in the BATSE data while there are only two outliers to the EpEi relation in the current sample of bursts with confirmed redshifts? One possibility is that there are systematic errors. Since $d_2 \propto E_{\rm p,obs}^2$, if for some reason $E_{\rm p,obs}$ of all the BATSE bursts is overestimated by a factor of $\gtrsim$2 or if it is underestimated by the same factor for *BeppoSAX* and *HETE II* bursts, then the BATSE sample may be consistent with an EpEi relation. The other possibility is that the difference between the BATSE data and the current sample of bursts with confirmed redshifts results from an observational selection effect (Lloyd-Ronning & Ramirez-Ruiz 2002). This explanation is supported by the fact that both outliers were not localized in the usual manner by either *BeppoSAX* or *HETE II* whose localized bursts compose the sample of bursts with known redshift used to derive and test the EpEi relation. The first, GRB 980425, was detected and localized by *BeppoSAX*. However, if it were not for the discovery of SN 1998bw (Galama et al. 1998), the identification of its host galaxy and the measurement of its redshift would have remained questionable. The second outlier, GRB 031203, was localized by *INTEGRAL* (Sazonov, Lutovinov & Sunyaev 2004). Observational selection effects might play a complicated role, especially since the threshold for redshift measurement might be higher than the threshold for detection. This is intuitively clear as the redshift determination requires not only a detection of the prompt emission but also a fast localization and an afterglow detection.

Our results suggest that *Swift*, which is expected to reduce the threshold for detection, localization and afterglow detection, will detect dim and hard bursts that do not satisfy the EpEi relation. It is impossible, however, to quantify this prediction without a clear understanding of the threshold for redshift measurement. Moreover, this second threshold would have to be understood in order to use the coming sample of *Swift* bursts with known redshifts to study the relation between $E_{\rm p}$ and $E_{\rm iso}$, or other intrinsic properties of the GRB population.

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REFERENCES

Amati L. et al., 2002, A&A, 390, 81
Atteia J.-L., Ricker G. R., Lamb D. Q., Sakamoto T., Graziani C., Donaghy T., Barraud C., The Hete-2 Science Team, 2004, in Fenimore E. E., Galassi M., AIP Conf. Proc. 727, Gamma-Ray Bursts: 30 Years of Discovery. Am. Inst. Phys., New York, p. 37
Band D. et al., 1993, ApJ, 413, 281
Band D. L., Preece R. D., 2005, ApJ, in press (astro-ph/0501559)
Galama T. J. et al., 1998, Nat, 395, 670
Ghirlanda G., Ghisellini G., Lazzati D., 2004a, ApJ, 616, 331
Ghirlanda G., Ghisellini G., Celotti A., 2004b, A&A, 422, L55
Jimenez R., Band D., Piran T., 2001, ApJ, 561, 171
Lamb D. Q., Donaghy T. Q., Graziani C., 2004, New Astron. Rev., 48, 459
Lloyd N. M., Petrosian V., Mallozzi R. S., 2000, ApJ, 534, 227
Lloyd-Ronning N. M., Ramirez-Ruiz E., 2002, ApJ, 576, 101
Sakamoto T. et al., 2004, ApJ, submitted (astro-ph0409128)
Sazonov S. Y., Lutovinov A. A., Sunyaev R. A., 2004, Nat, 430, 646
Stern B. E., Tikhomirova Y., Stepanov M., Kompaneets D., Berezhnoy A., Svensson R., 2000, ApJ, 540, L21

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